NPDGamma Liquid Hydrogen Engineering Document

7-05
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Introduction (M. Snow, 6-20-01)

This document consists of a general description of the design, operation, and safety aspects of the liquid parahydrogen target for the NPDGamma experiment. The purpose of this experiment is to search for parity violation in the angular distribution of 2.2 MeV gammas produced by polarized cold neutron capture in hydrogen. The experiment therefore requires a hydrogen target. For the purposes of this document we will define the "target" broadly to include (1) the target cryostat and vacuum system inside the experimental cave, where the neutron captures take place, (2) the gas handling and target control system external to the cave, and (3) the safety system external to the cave, including the relief valves and blowoff stack. A conceptual sketch of these components of the overall system is shown in Figure 1.

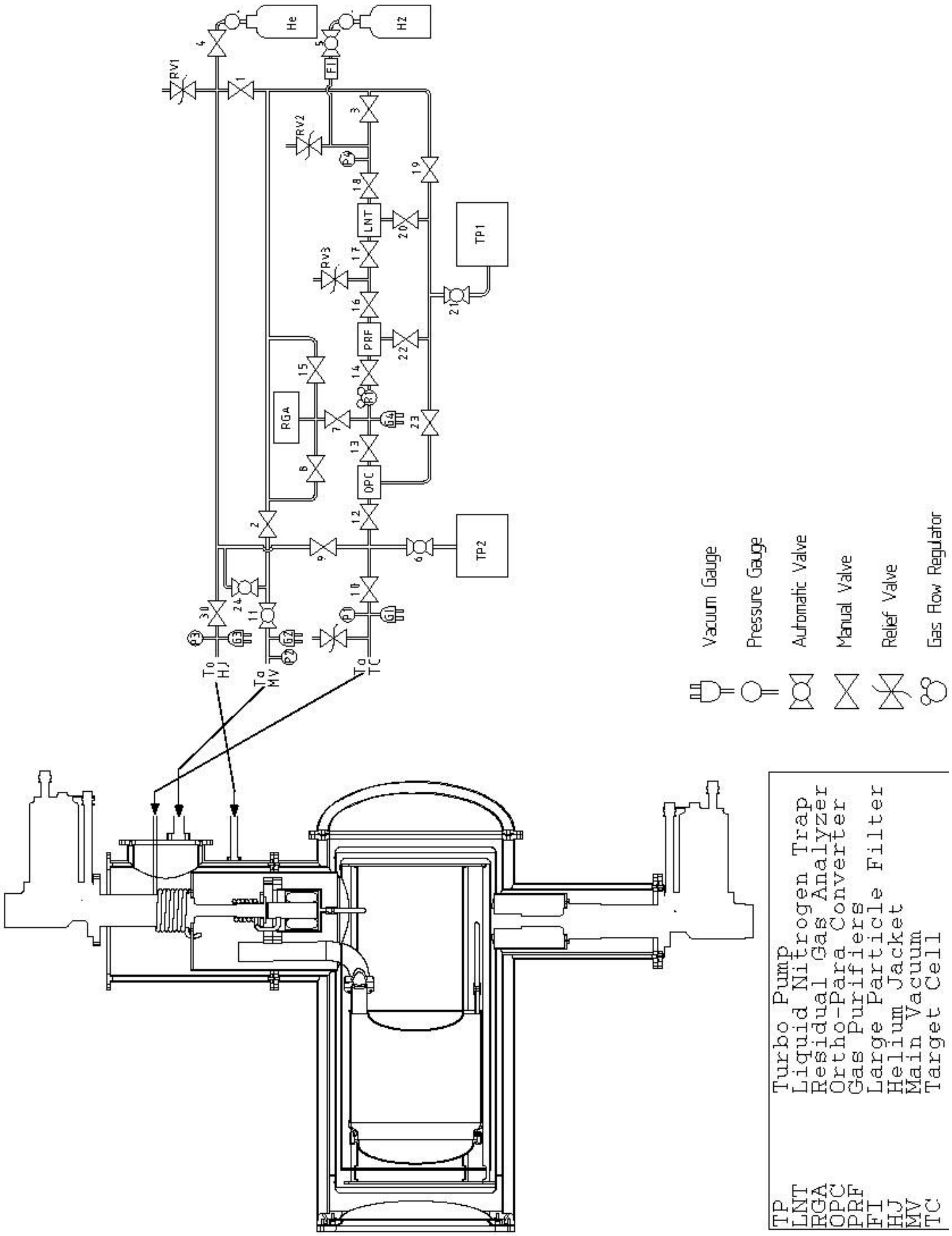

Figure 1: Target and Gas Handling System

A LH2 Target for NPDGamma (M. Snow, 6-20-01)

We begin with a brief description of the physics goals of the experiment. The goal of this experiment is to search for a parity violating asymmetry in the angular distribution from polarized cold neutron capture on protons with a sensitivity of 5 ppb. To reach this level of statistical accuracy will require operation of the experiment at the LANSCE neutron source for a live time of approximately one year. In addition, we must insure that there exists no other effect in the experiment which introduces an asymmetry in the apparatus which does not come from the reaction of interest. Our goal is to limit the size of all such possible “false” effects to a size of 0.1 ppb. A detailed description of the means by which the overall experiment plans to achieve these goals is included in the DOE proposal. This and other documents relevant to the physics goals of the experiment and the current status of progress toward those goals can be found on the website http://p23.lanl.gov/len.

Design goals for the target (M. Snow, 6-20-01)

The physics goals of the experiment coupled with the known properties of cold neutron and MeV gamma interactions with materials, the properties of hydrogen, and the need for the target system to be consistent with the other subsystems of the experiment implicitly define the following design goals for the target:

(1) The target must absorb as much of the polarized cold neutron beam flux as possible without depolarizing the neutron beam before capture. The need to prevent neutron depolarization requires the target to consist of parahydrogen at a temperature no higher than 17K. Given the 10 cm x 10 cm size of the beam at LANSCE, the phase space of the beam from the LANSCE cold neutron guide using 3m supermirror neutron guides, and the scattering cross section of cold neutrons in parahydrogen, the target size of 30 cm diameter and 30 cm length has been chosen on the basis of Monte Carlo simulations using MCNP and the LANL hydrogen neutron scattering kernel. This target will absorb 60% of the incident cold neutron flux. The target system therefore requires a cryostat to liquefy gaseous hydrogen at room temperature and an ortho-para converter to catalyze the formation of parahydrogen.

(2) The target must possess negligible attenuation of the 2.2 MeV gammas from neutron capture. This requires the use of low Z materials in the target vessel and associated radiation shields and vacuum vessel.

(3) To ensure that the statistical accuracy of the measurement is not compromised by extra noise due to density fluctuations in the target, we require a liquid target in which bubbles are suppressed to acceptable levels and in which fluctuations in the pressure and temperature of the target are held to acceptable levels. The suppression of bubbles will be insured by the following design features: (a) the use of a second cryostat which will be capable of cooling the radiation shield surrounding the target vessel to a temperature below 17K, thereby reducing the heat load on the 17K target vessel, (b) the use of a heater on the exhaust line of the target which can maintain the pressure in the (recirculating) target chamber at a value above that of the equilibrium vapor pressure at 17K (in other words, the target is superheated), and (c) the use of a neutron-absorbing cylindrical bubble shield which will deflect any bubbles which might be released from the inner surface of the target chamber out of the neutron beam.

(4) To ensure that no false effects are introduced by gammas produced by polarized slow neutron capture on target materials other than parahydrogen, we must select the target vessel material carefully. Estimates have shown that neutron absorption of the full

beam in Al is unacceptable. The window materials seen by the neutron beam will consist of Ti and a Mg alloy on the target vessel itself. The remainder of the target chamber, although made of Al, is protected from polarized neutron capture by a 6Li-rich neutron shield inside the target chamber. This shield will possess an exit hole which will be small enough for polarized neutron capture in the Al exit window to produce a negligible systematic effect but large enough to permit efficient monitoring of the neutron beam exiting the target.

(5) To ensure that interaction of the circular polarization of the gammas produces negligible systematic effects and that the magnetic field in the target can be maintained with sufficient uniformity, the target materials in the vicinity of the neutron beam must be nonmagnetic. Any magnetic components in the target system must result in negligible magnetic field gradients.

Responsibilities (M. Snow, 6-20-01)

The target will be designed, constructed, and operated jointly by NPDG collaborators at Indiana University and Los Alamos. The details of the division of responsibilities are discussed in a Memorandum of Understanding (MOU) which is included in the Appendix. Roughly speaking, Indiana University has the major responsibility for target design, construction, and non-LH2 testing at Indiana and LANL has the main responsibility for target safety and the integration and final testing of the system at LANL.

Target Design (M. Snow. M. Gericke, H. Nann, 6-20-01)

Here we describe the overall design of the target system, including important parameters when required but not including the detailed design calculations which are outlined later in the document in selected cases. We will organize the discussion by following the hydrogen during the filling process. We will restrict our description to the filling procedure and steady state operation of the target with some general comments on the main safety features. Refer to Figure 1.

The hydrogen starts from a 2000 psi compressed gas cylinder with an ortho-para ratio appropriate to room temperature in thermodynamic equilibrium (3:1). This cylinder will be located outside of the experimental building. The gas will exit through a gas pressure regulator and an automatic valve which will close in the event of an appropriate warning signal. The fill line will be conducted into the experimental hall and connect to a gas handling system located close to the experimental cave. The hydrogen will pass through a particulate filter, a liquid nitrogen trap to remove water and other contaminants, a gas purifier (probably based on a palladium leak) to reduce the concentration of gases other than hydrogen to ppb levels, and an ortho-para conversion chamber based on chromic oxide (CrO3) powder and operated at 77K for partial conversion of the gas before entering the refrigerator. All of the modules associated with cleaning and converting the gas can be isolated with manual valves for necessary activation (which typically involving some combination of baking and a pump/purge cycle). The gas flow rate,which is determined by the cooling power of the refrigerators and the properties of hydrogen (see below), will be 10 standard liters/minute.

In addition to the hydrogen line, the gas handling system will also possess two other lines connected to the target system: a main vacuum line for evacuation of the system and a helium gas line to supply the helium jacket around the target, leak test all vacuum components, and flush the system before cooldown. A residual gas analyzer on the gas handling system will be used to monitor the purity of the hydrogen, to act as a helium leak detector during target testing prior to cooling, and to monitor the main vacuum gas composition for helium, hydrogen, and other gases during operation. Pressure gauges on the gas handling system will monitor the pressure in the target, helium jacket, and main vacuum. An electrical feedthrough on the gas handling system will provide signals from all required transducers in the target, such as thermometers and the LH2 liquid level meter. With the necessary exception of the liquid level, which of course must be located inside the liquid hydrogen chamber, all other transducer signals from the target possess wiring that is located in the main vacuum chamber. Turbopumps on the gas handling system will be used to evacuate the target chambers. The pumps will be isolated from the target vacuum with an automatic valve during filling and manually during steady-state operation to prevent loss of vacuum to the target during a power failure. The plumbing on the gas handling system will be composed of welded components and VCR-based joints constructed to typical (10E-9 atm*cc/sec) helium leak tight specifications. Blowoff and vent valves will be present at all required locations. All plumbing lines entering the target will possess ceramic sections for electrical isolation.

The cooled and preconverted hydrogen gas enters the experimental cave through a reentrant hole in the shielding. It passes through the helium jacket into the main vacuum and is thermally connected to both cooling stages of a GM-based cryorefrigerator. The refrigerator is located inside the cave and its associated compressor is located outside the cave. This refrigerator possesses a cooling power of 60 watts at the 77K stage and 12 watts at the 20K stage. This is sufficient to liquefy the hydrogen and perform the ortho-para conversion for the given flow rate (calculation below). The liquid hydrogen enters another ortho-para conversion chamber at the cold stage. Gas produced by the heat of conversion is recondensed in the chamber and passes through the chamber in a recirculating fashion until essentially all (99.8% at 20K) of the liquid in the target is converted to the para state.

The liquid parahydrogen flows down a narrow fill line into the bottom of a 20 liter cylindrical target chamber. The chamber is wrapped with heater wire and superinsulation, surrounded by a thermally-insulating support structure made of G-10 rods,and supported by a radiation shield which is cooled by a second GM cryorefrigerator. Thermal connection of both refrigerators to the target chamber and radiation shields is effected by both mechanical connection to the cold stage flanges and, where necessary, by flexible copper braid. A similar support structure separates the two radiation shields and the outer radiation shield from the inside of the main vacuum chamber. This support structure allows the liquid target chamber to slide horizontally upon thermal contraction. Stress on the target from differential thermal contraction in the vertical direction is accommodated with the use of a curved fill line on the inlet and a formed stainless bellows on the outlet line of the target. Stress on the radiation shields due to differential thermal contraction in the vertical direction is accommodated by the flexibility of the thin walls of the radiation shields.

There are three vacuum flanges on the target chamber: two small flanges on the inlet and outlet lines and one large flange on the entrance. The inside of the target chamber includes a cylindrical neutron shield loaded with 6Li to prevent polarized neutron capture on the Al target vessel with a 10 cm x 10 cm entrance hole for the neutron beam and a much smaller exit hole for monitoring purposes downstream of the target. In addition, there is a LH2 liquid level meter consisting of a series of resistors which extends from the bottom of the target into the exhaust line to the height of the ortho-para converter. Given the cooling powers stated above and the known thermodynamic properties of hydrogen, we estimate a filling time for the target of about 2 days.

The exhaust line from the target possesses a large diameter (1.5”). This exhaust line passes through the top flange of the cryocompressor and to the outside of the cave, where it is connected to a blowoff stack that vents to a location outside the building on the roof. The diameter of this line has been determined by a series of calculations outlined below to insure that there is no release of liquid hydrogen in the event of a loss of vacuum. The verification of these calculations will be the subject of test measurements described below. In addition, the main vacuum also possesses a similar vent line (2.5” diameter) which ensures that there is no release of hydrogen in the event of a rupture of the target. Finally, there will be a vent line for the 4He jacket (0.75” duameter).

The liquid fills the target chamber and also a portion of the exhaust line. The exhaust line is thermally isolated from the target vessel with a section of tubing made of nonmagnetic stainless steel. This section of the exhaust line possesses a heater which is used to locally heat the liquid. Due to the low thermal conductivity of the liquid parahydrogen and the tubing, it is possible to maintain a small temperature gradient in the liquid in the exhaust line. The heater performs two functions: (1) it maintains the gas pressure in the target chamber at a value higher than the equilibrium vapor pressure of the liquid seen by the neutron beam, thereby superheating the target and suppressing bubble formation, and (2) it induces the circulation of hydrogen through the target through a small-diameter connection which reintroduces the evaporated gas back into the target fill line and back through the ortho-para converter. In this way when the target is full and in steady-state operation, it is bubble-free and continuously reconverted to liquid parahydrogen.

The thermodynamic state of the target is determined using pressure measurements and temperature measurements on the target, cryorefrigerators, ortho-para converter, and exhaust line. This information is relayed to a control system outside the cave which provides feedback heat to the refrigerators to maintain the temperatures in the required range.

Main Safety Aspects of the Design (M. Snow, H. Nann, 6-20-01)

The size of the liquid hydrogen target (approximately 20 liters) coupled with its location in a confined space during the experiment (a cave for neutron and gamma shielding), the need for access in the cave while the target is full, and the presence of several electrical systems inside the cave in other parts of the apparatus, dictate certain safety requirements. A preliminary assessment of the safety requirements for this target was performed in 1999 at LANL. The Appendix contains the main recommendations of the committee, which evaluated a preliminary conceptual design of the target. Because of the preliminary nature of the design at that time, certain details of the recommendations of the committee are no longer relevant to the current design. The next safety review, required before construction of the target can begin, will be held at Indiana University in August 2001. The main recommendations of the 1999 safety committee were as follows:

(1) The target must be designed so that no release of hydrogen into the experimental cave occurs in the event of either a failure of the main vacuum system or a failure of the target vessel.

(2) All parts of the target vacuum system inside the cave must be surrounded by a helium jacket.

These recommendations have been incorporated into the detailed design of the target system outlined in this report. Here we summarize the results of our analysis of the most serious safety issue: response of the system to catastrophic vacuum or target failure. Details of the calculations are included in the appendix.

Hydrogen-air mixtures in concentrations ranging from 4% to 75% of H_2 by volume are highly explosive. Normally a spark of some kind is needed for ignition, but hydrogen vapor escaping from leaks has been known to spontaneously combust. It is, therefore, of paramount importance to eliminate the possibility of explosive hydrogen-air mixtures occurring and to prevent ignition. The mechanical aspects of the liquid hydrogen (LH_2) target system are designed to minimize the possibility of a hydrogen release into the experimental cave and hall in case of a leak or rupture due to overpressure. A control system is developed to allow the careful monitoring of the target system behavior and to respond to any aberration from normal operating conditions.

The liquid hydrogen target system consists of three components ("triple containment"). The LH_2 target flask connected to the condenser unit by a filling and a vapor escape line is contained inside a vacuum vessel, which provides, together with two radiation shields cooled at 17 K and 100 K, thermal insulation. A helium jacket surrounds the vacuum vessel and the hydrogen piping system to the outside of the experimental cave with the helium at a higher pressure than the surrounding atmosphere. This helium jacket has a dual purpose. First, if a leak occurs in the wall of the vacuum vessel, it can be detected immediately by a RGA monitoring the vacuum. Second, the helium jacket prevents air or other gases from penetrating into the vacuum through such leaks. If gases other than helium (and hydrogen) get in contact with the LH_2 flask or the hydrogen piping from the refrigerators to the target, they will immediately freeze. Solidified gases are difficult to detect, as they will not produce a pressure increase. Solid oxygen and nitrogen will radiolyse in the radiation field around the LH_2 target and form compounds that can self-ignite.

There are several maximum credible accidents possible.

(1) A loss of either refrigeration or vacuum will lead to a rapid boiling in the target flask and cause the pressure in the condenser-target system to rise. In the case of overpressure buildup, a pressure relief system, consisting of a safety relief valve and a rupture disc in parallel, will release the hydrogen gas into a vent line that exhausts through the roof of the building high up into the outside atmosphere. This vent line is an 6-inch diameter, 304 or 304L stainless steel tube closed toward the outside atmosphere by a leak tight check valve and filled with nitrogen at 1 atm.

(2) A rupture of the target flask or piping inside the vacuum vessel will release the LH_2 into the vacuum and hydrogen will boil off. Again when overpressure through the rapid boil off occurs, a pressure relief system will safely release the hydrogen gas into the vent line and the outside of the building while maintaining the pressure within the target vessel at a safe level. It should be mentioned that during normal operation the vacuum pump is isolated from the vacuum vessel.

(3) In case of fire in the experimental area or for some other reasons, the LH_2 in the target flask has to be disposed off very quickly. This will be done by filling the vacuum vessel with helium and by electrically heating the lateral surface of the target flask, thus letting the LH_2 boil off at a controlled rate. This scenario is similar to the one described under (1) above, but with more heat flowing into the target flask.

Each of the three components of the LH_2 target system has a separate pressure relief system, which is sufficiently robust to respond safely to any maximum credible accident. The conductance of each safety relief system has to be large enough that a pressure rise will not lead to a rupture of the component. Calculations based on the Bates Internal Report # 90-02 were performed to determine the size of the relief plumbing such that the mass flow remains subsonic at all times and that the maximum pressure in each component remains well below its bursting point. The final results show that, in the case of a catastrophic vacuum failure to air, the target flask is subjected to a pressure of no more than 43 psia if the inner diameter of the pressure relief piping is 1.5 inch. The maximum pressure in the vacuum vessel for the case of a rupture of the target flask is 40 psia for an inner diameter of the pressure relief piping is 2.5 inch. Both pressures are well below the 100 psia pressures that the target flask and vacuum vessel will be tested at. Since the pressure relief system for the vacuum vessel can respond safely to a possible catastrophic rupture of the target flask, the pressure relief system of the helium jacket does not need to handle a large mass flow rate in the unlikely event of a leak in the wall between the vacuum vessel and the helium jacket. Thus a pressure relief system with an inner diameter of 0.75-inch piping is considered adequate.

In summary, pressure relief systems with a 1.5-inch inner diameter discharge pipe for the target flask and a 2.5-inch inner diameter discharge pipe for the vacuum vessel will respond safely to catastrophic failures. Furthermore, the safety relief piping for the helium jacket will have an inner diameter of 0.75 inch.

Various gas monitoring systems must be active to ensure that an explosive mixture does not occur in the first place. We propose to monitor the vacuum space for hydrogen, helium, and oxygen with a RGA. We believe that there is no need to monitor the helium jacket for hydrogen, since hydrogen will be detected in the main vacuum long before it is seen in the helium jacket.

Quality Management Plan

Design

This section consists of a detailed description of the specifications of the NPDGamma liquid hydrogen target system as of July 2001. The final specifications may change as a result of (1) the finite-element calculations on the target vessel conducted by the ARES Corporation (in progress), and (2) the target safety review in August 2001 at IUCF.

Cryostat and vessels

- **specifications (M. Snow, 6-15-01)**

Table 1 lists the main mechanical specifications of the target vessel, main vacuum, helium jacket, and radiation shields.

Table 1: Specifications of LH2 target, radiation shields, main vacuum, and He jacket.

Object	Mechanical Properties			Connections
	Dimensions	Material	Fabrication	
LH2 target vessel	30 cm diameter 30 cm length 0.25 cm thickness	5083-O Al body AZ31C-H24 Mg entrance window	Cylindrical Al body welded from cold-rolled sheet. Inlet and outlet flanges welded. Mg window machined from plate (no Mg welds)	30 cm diameter flange for Mg-Al connection, Mylar seal 1.2 cm diameter liquid inlet flange, Al Conflat seal 3.8 cm diameter outlet flange, Al Conflat seal
Radiation shield, stage 2	33.5 cm diameter 71 cm length 0.1 cm thickness	OFHC Cu	Soldered from cold-rolled and annealed sheet.	6 cm diameter mechanical connection to refrigerator #2
Radiation shield, stage 1	36 cm diameter 80 cm length 0.1 cm thickness	OFHC Cu	Soldered from cold-rolled and annealed sheet	22 cm diameter mechanical connection to refrigerator #1 and 8 cm diameter connection to refrigerator #2
Main Vacuum Vessel	40 cm diameter 94 cm length 0.25 cm thickness	5083-O Al body unalloyed Ti entrance window	Cylindrical Al body welded from cold-rolled sheet. Inlet and outlet flanges welded. Ti window formed from plate (no Ti welds)	2.5 cm diameter flange to external pump and GHP
Helium Jacket	45 cm diameter 98 cm length 0.1 cm thickness	5083-O Al body unalloyed Ti entrance window. 40 cm I.D. 45 cm O.D. internal braces	Cylindrical Al body welded from cold-rolled sheet. Inlet and outlet flanges welded. Al braces	0.6 cm diameter line to GHP

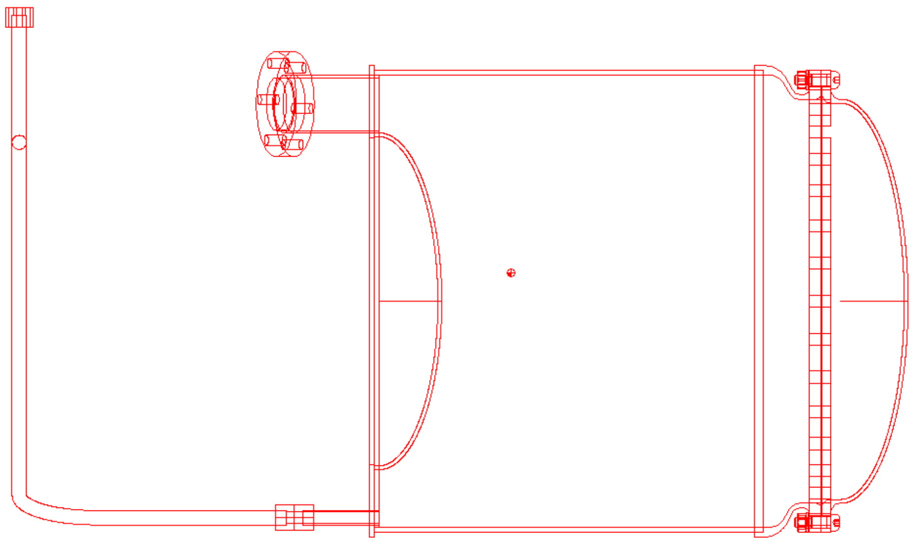

Figure 2: Liquid Hydrogen Target Vessel

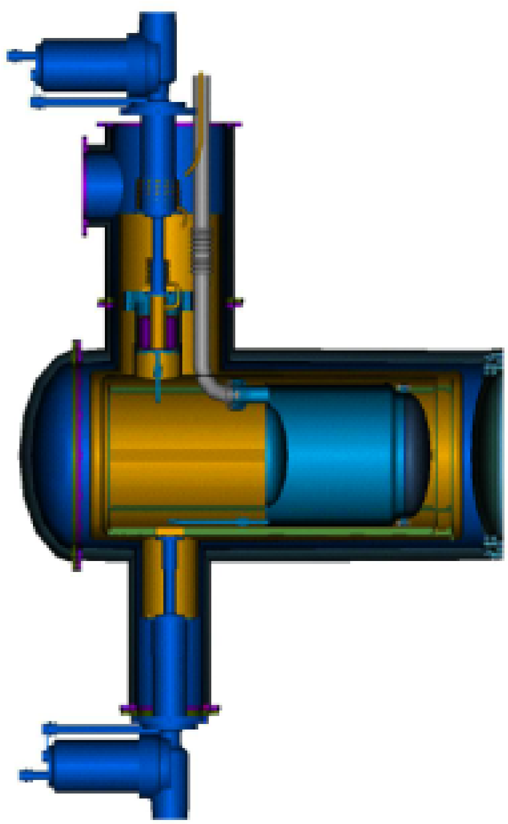

Figure 3: Target Assembly

- **strength calculations: LH2 target Mg alloy window (H. Nann, 6-20-01)**

The minimum required thickness for the Mg window on the LH_2 target flask was calculated according to the ASME Code, Section VIII, using design pressure, allowable stress, and the design formulas compatible with the geometry.

Allowable stress:

The maximum allowable stress was taken as the smaller of $\frac{2}{3}S_y$ or $\frac{1}{4}S_u$, where S_y is the minimum specified yield strength of the material at room temperature and S_u the minimum specified ultimate strength of the material at room temperature.

For the magnesium alloy AZ31C-H24: S_y = 29000 psi, S_u = 39000 psi

Thus $\frac{2}{3}S_y$ = 19300 psi

$\frac{1}{4}S_u$ = 9750 psi

Code formulas for calculation of vessel component thickness:

List of symbols used in the formulas below:

t = minimum thickness [inch]	
p = internal design pressure [psi];	assume p = 75 psia
R = inside radius [inch];	R = 6.0 inch
D = inside diameter [inch]	D = 12.0 inch
S = allowable stress [psi]	assume S = 9750 psi
E = weld joint efficiency factor	assume E = 1.0 (no weld)

Ellipsoidal head (2:1), pressure on concave side

$$t = \frac{pD}{2SE - 0.2p} \qquad \text{or} \qquad p = \frac{2SEt}{D + 0.2t}$$

Thus

$$t = \frac{(75)(12.0)}{2(9750)(1.0) - (0.2)(75)} = 0.046 \text{ inch}$$

CONCLUSION: Use *t = 0.1* inch as flask wall thickness.

Now use the above formula for p to calculate the maximum allowable pressure for a wall thickness of *t = 0.1* inch.

p = 162 psia

o strength calculations: LH2 target Al alloy flask (H. Nann, 6-20-01)

The minimum required thickness for the LH2 target flask was calculated according to the ASME Code, Section VIII, using design pressure, allowable stress, and the design formulas compatible with the geometry.

Allowable stress:

The maximum allowable stress for 5083-O aluminum alloy was taken from table ULT-23 of the ASME Code, Section VIII: S = 10000 psi

Code formulas for calculation of vessel component thickness:

List of symbols used in the formulas below:

t = minimum thickness [inch]	
p = internal design pressure [psi];	assume p = 75 psia
R = inside radius [inch];	R = 6.0 inch
D = inside diameter [inch]	D = 12.0 inch
S = allowable stress [psi]	assume S = 10000 psi
E = weld joint efficiency factor	assume E = 1.0

(A) Cylindrical shell under internal pressure

(1) circumferential stress (longitudinal joints)

$$t = \frac{pR}{SE - 0.6p} \qquad \text{or} \qquad p = \frac{SEt}{R + 0.6t}$$

Thus

$$t = \frac{(75)(6.0)}{(10000)(1.0) - (0.6)(75)} = 0.045 \text{ inch}$$

(2) longitudinal stress (circumferential joints)

$$t = \frac{pR}{2SE + 0.4p} \qquad \text{or} \qquad p = \frac{2SEt}{R - 0.4t}$$

Thus

$$t = \frac{(75)(6.0)}{2(10000)(1.0) + (0.4)(75)} = 0.022 \text{ inch}$$

(B) Ellipsoidal head (2:1), pressure on concave side

$$t = \frac{pD}{2SE - 0.2p} \qquad \text{or} \qquad p = \frac{2SEt}{D + 0.2t}$$

Thus

$$t = \frac{(75)(12.0)}{2(10000)(0.8) - (0.2)(75)} = 0.045 \text{ inch}$$

CONCLUSION: Use *t = 0.1* inch as flask wall thickness.

Now use the above formulas for p to calculate the maximum allowable pressure for a wall thickness of *t = 0.100 (0.125)* inch.

(A1) p = 165.0 (205.8) psia

(A2) p = 335.6 (420.2) psia

(B) p = 166.4 (207.9) psia

o strength calculations: vacuum vessel (H. Nann, 6-20-01)

The minimum required thickness for the vacuum vessel surrounding the LH2 target flask was calculated according to the ASME Code, Section VIII, using design pressure, allowable stress, and the design formulas compatible with the geometry.

Allowable stress:

The maximum allowable stress for 5083-O aluminum alloy was taken from table ULT-23 of the ASME Code, Section VIII: S = 10000 psi

Code formulas for calculation of vessel component thickness:

List of symbols used in the formulas below:

t = minimum thickness [inch]	
p = internal design pressure [psi];	assume p = 75 psia
R = inside radius [inch];	R = 8.0 inch
D = inside diameter [inch]	D = 16.0 inch
S = allowable stress [psi]	S = 10000 psi
E = weld joint efficiency factor	assume E = 1.0

(A) Cylindrical shell under internal pressure

(1) circumferential stress (longitudinal joints)

$$t = \frac{pR}{SE - 0.6p} \qquad \text{or} \qquad p = \frac{SEt}{R + 0.6t}$$

Thus

$$t = \frac{(75)(8.0)}{(10000)(1.0) - (0.6)(75)} = 0.060 \text{ inch}$$

(2) longitudinal stress (circumferential joints)

$$t = \frac{pR}{2SE + 0.4p} \qquad \text{or} \qquad p = \frac{2SEt}{R - 0.4t}$$

Thus

$$t = \frac{(75)(8.0)}{2(10000)(1.0) + (0.4)(75)} = 0.030 \text{ inch}$$

(B) Ellipsoidal head (2:1), pressure on concave side

$$t = \frac{pD}{2SE - 0.2p} \quad \text{or} \quad p = \frac{2SEt}{D + 0.2t}$$

Thus

$$t = \frac{(75)(16.0)}{2(10000)(1.0) - (0.2)(75)} = 0.060 \text{ inch}$$

CONCLUSION: Use *t = 0.125* inch as wall thickness for the vacuum vessel .

Now use the above formulas for p to calculate the maximum allowable pressure for a wall thickness of *t = 0.125* inch.

(A1) p = 154.8 psia

(A2) p = 314.5 psia

(B) p = 156.0 psia

- **finite element analysis**

The result of the finite element analysis on the LH2 vessel performed by the ARES Corp. is included in an appendix.

- **material data sheets (M. Snow)**

Copies of the relevant material data sheets are in the Appendix. All of the materials listed above are approved materials for use with liquid hydrogen as specified in the NASA safety references.

- **welding certificates**
- **vacuum checking (M. Snow)**

The LH2 target vessel, main vacuum, helium jacket, and all associated joints will be helium leak tight at all temperatures encountered on the 10E-9 bar-cc/sec level. The radiation shields are not vacuum enclosures and will include reentrant vent holes to allow efficient pumpdown of the main vacuum.

- **design pressures (H. Nann, 6-20-01)**

Table 2 lists the vessels which will be pressure tested, the operating, working, and design pressures, the maximum internal pressures, and the proposed settings for rupture disks and pressure relief valves. All components will be tested to their design pressures. Recall that atmospheric pressure at LANL is 11 psia.

Table 2: Important Pressures Associated with the Hydrogen, Helium, and Vacuum vessels

Object					
	Normal Operating Pressure	Maximum Internal Pressure (from CODE)	Maximum Allowable Working Pressure and Design Pressure (from CODE)	Pressure Relief Valve Setpoint	Rupture Disk Setpoint
LH2 target vessel with Mg window	10 psia	160 psia	70 psig (81 psia at LANL), 96 psia	7 psig (18 psia at LANL)	75 psig (86 psia at LANL)
Main Vacuum Vessel	vacuum	150 psia	70 psig (81 psia at LANL), 90 psia	20 psig (31 psia at LANL)	75 psig (86 psia at LANL)
Helium Jacket	18 psia	150 psia	70 psig (81 psia at LANL), 90 psia	25 psig (36 psia at LANL)	75 psig (86 psia at LANL)

- **low temperature seals (M. Snow, 2-22-01)**

There will be three flanges on the target flask. The smaller flanges are aluminum Conflat flanges using Al bolts and Al sealing rings. Such seals are known to be reliable at cryogenic temperatures. The larger flange,which joins the Al body of the chamber to the Mg entrance window, is sealed with Mylar. Mylar is CODE-approved and is a common material in liquid hydrogen targets. (Since Mg possesses a slightly larger thermal contraction than Al, it is necessary to use Al bolts and low thermal-contraction washers, probably tungsten, on this seal to ensure vacuum integrity at low temperature. We have successfully constructed tungsten washers in the Indiana machine shops.) Mylar selas are also known to be effective at cryogenic temperatures. In addition, we intend to use a flange design outlined in the literature which has been proven to withstand internal pressures of 20 bar at 77K.

Relief System and Vent Line

- **specifications (H. Nann, 6-20-01)**

Table 3 contains a list of the various parts of the relief system along with their performance requirements. Each component from the individual enclosures will possess a primary relief system consisting of a spring-loaded pressure relief valve and a secondary relief system consisting of rupture disk in parallel with the relief valve. All pressure reliefs are connected to a large (6" diameter) vent line which is filled with nitrogen gas at atmospheric pressure and conducts the gas to the outside of the experimental hall.

Table 3: Specifications of Vent Lines and the Vent Stack

Vent Lines	Mechanical and Conductance Properties of Vent Lines/Blowoffs			Pressure in Worst-Case Failure
	Dimensions	Material	Flow Capacity	
LH2 target vent line	1.5 “diameter XX cm length	304 stainless steel	0.20 lb/sec	43 psia
Main Vacuum vent line	2.5” diameter XX cm length	304 stainless steel	0.50 lb/sec	43 psia
Helium jacket relief valve	0.75” diameter XX cm length	304 stainless steel	0.05 lb/sec	
Vent stack	6” diameter XX cm length	304 stainless steel		

- **design and dimensional calculations (H. Nann, 6-20-01)**

  The following are results of calculations based on the formulas and procedures of the Bates Internal Report # 90–02, Sept 1990, W. Schmitt and C. Williamson “Boiloff Rates of Cryogenic Targets Subjected to Catastrophic Vacuum Failure”.

Pressure Rise due to Catastrophic Failure of Vacuum

Assume: Flow temperature T = 293 K
Outlet pressure p_2 = 15 psia
Effective length of vent line L/d = 500
Equivalent resistance K = 10

Results:

Mass flow rate [lb/s]	w =	0.05	0.10	0.10	0.10	0.15	0.20	0.30	0.30
ID of vent pipe [inch]	d =	1.0	1.0	1.125	1.5	1.125	1.5	1.5	1.75
Sonic flow rate [lb/s]	w_{sonic} =	0.13	0.13	0.16	0.29	0.16	0.29	0.29	0.40
Inlet pressure [psia]	p_1 =	28.4	52.5	42.1	26.0	61.9	47.0	69.5	51.4

Pressure Rise due to Rupture of LH_2 Flask

Assume: Flow temperature T = 293 K
Outlet pressure p_2 = 15 psia
Effective length of vent line L/d = 500
Equivalent resistance K = 10

Here the LH_2 is in contact with larger warm surface area _ larger boil-off rate and thus larger mass flow rate.

Results:

Mass flow rate [lb/s]	w =	0.5	0.5	0.75
ID of vent pipe [inch]	d =	2.0	2.5	2.5
Sonic flow rate [lb/s]	w_{sonic} =	0.52	0.82	0.82
Inlet pressure [psia]	p_1 =	65.2	42.6	62.7

For our chosen parameters, the maximum pressure in either vessel under either scenario is 43 psia. This is less than half of the design pressure for each vessel.

- **data sheet**
- **test procedures (H. Nann, 6-20-01)**

The following tests will be performed to verify the design parameters calculated above. These tests will be performed at IUCF.

(1) Test each component hydrostatically up to 100 psig. The calculated internal design pressure for the target flask is 160 psia and for the vacuum vessel 150 psia.

(2) Test of overpressure behavior and sizing of the safety relief devices of the LH_2 target system by controlled spoiling of the insulating vacuum with air. (A similar test has been performed at JLAB with their cryomodules: M. Wiseman et al., Applications of Cryogenic Technology, Vol. 10, Edited by J.P. Kelley, Plenum Press, New York, 1991). The procedure is as follows:
(a) Pressure relief valve is set at 7 psig (= 21.7 psia at Bloomington, IN) and rupture disc at 75 psig.
(b) Instrument target flask, buffer volume, and exhaust line just upstream of relief devices with pressure and temperature transducers and recorders.
(c) Fill target flask with LN_2 at atmospheric pressure.
(d) Bleed air into insulating vacuum through calibrated needle valve to control flow rate.
(e) From pressure and temperature response versus time determine maximum N_2 mass flow rate through relief valve and piping system.

(f) Calculate maximum H_2 mass flow rate using latent heat of evaporation for N_2 (160 kJ/L) and H_2 (31.8 kJ/L).

(3) Test overpressure behavior and sizing of the safety relief devices of the vacuum vessel by suddenly dumping 20 L of LN_2 into it.

(a) Pressure relief valve is set at 20 psig and rupture disc at 75 psig.

(b) Instrument vacuum vessel with pressure transducers and recorders.

(c) Replace magnesium entrance dome of the target flask with a similar size aluminum plate that has a thin Mylar window.

(d) Fill the target flask with LN_2 at atmospheric pressure.

(e) Rupture the Mylar window with a motorized knife.

(f) Record pressure versus time.

H2 gas manifold

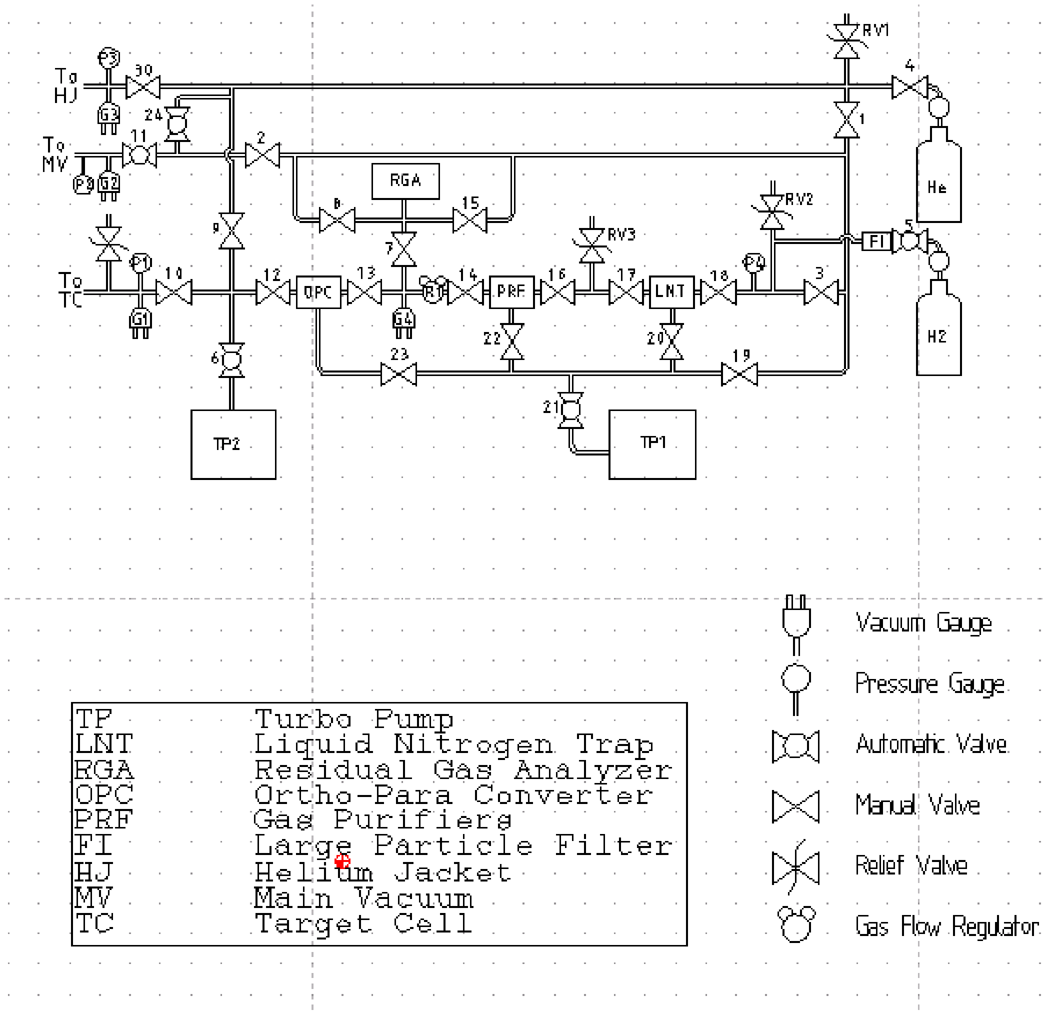

Figure 4: Gas Handling System

- **specifications (M. Snow, M. Gericke, 7-1-01)**

Table 4 lists the main components of the H2 gas handling system and their relevant properties. The plumbing will be constructed either of stainless steel components with VCR connections of welded tubing.

Table 4: Properties of major gas handling system components

Gas Handling Components	Relevant Properties			Function
	Inlet and outlet pressures	Material/Type	Operating and cleaning temperature	
Liquid N2 cold trap	150 psia inlet and outlet	304 stainless steel and OFHC copper	77K 150C	Trap water vapor and other freezable contaminants.
Flow rate meter	150 psia inlet and outlet	304 stainless steel	300K	Measure H2 gas flow rate
Hydrogen gas purifier	150 psia inlet 15 psia outlet	304 stainless steel body, palladium leak		Remove all non-hydrogen components to sub ppm concentration
Ortho-para Converter	15 psia inlet 15 psia outlet	CrO3 powder, OFHC copper container, porous copper inlet and outlet	77K 150C	Partial conversion of gas to parahydrogen state.
Residual gas analyzer	10E-3 torr inlet	Quadrupole RGA	300K	hydrogen gas purity, helium leak detection, gas monitoring of main vacuum
Turbopump	N/A		300K	evacuate target, main vacuum,helium jacket, and gas handling panel

- **design and operation (M. Gericke, 7-1-01)**

This is a description of the operation of the gas handling system (GHS) for the

NPDGamma liquid Hydrogen target. The GHS supplies the target with purified and ortho to para pre-converted H_2 gas. It facilitates purging the target with He, pumping down the Helium jacket (HJ), Main Vacuum (MV) and Target Cell (TC), monitoring of the gas supply to the cryo-refrigerators, monitoring of the MV and HJ pressures and continuous leak detection from both the TC and the HJ into the MV.

The GHS system consists of a He supply line, a MV control line, and the H_2 supply line. The H_2 supply line consists of a liquid nitrogen trap (LNT), a palladium leak hydrogen purifier (PRF), and an ortho to para pre-converter (OPC). The purification of the gas will start from 5N or 6N purity H_2 gas with the LNT to freeze out most impurities. Each of these components can be isolated from the rest of the system via a set of valves to provide for the possibility of component exchange/maintenance and bake-out. This enables one to ``clean" one part of the system without affecting the state of another. The palladium purifier will be used to extract impurities such as N_2, Ne, CH_2, CO, CO_2 and possibly others.

A residual gas analyzer (RGA) is placed in the GHS such that it can be used to monitor the gas purity in preparation for the ortho to para conversion and filling of the TC, as well as for leak checking in the MV area while the target is being filled and during the experiment itself. The OPC is the last component in the GHS, before the gas enters the target. Before the gas enters the target, the RGA can be used to monitor the gas purity.

With the exception of the ortho-para converter (discussed below) and the liquid nitrogen trap, all the components of the gas handling system will be constructed of commercial components.

The appendix contains a detailed set of procedures for operating the gas handling system, including the cleaning and leak testing of the target, the filling of the LH_2, and steady-state operation.

- **data sheets**
- **test results**

Ortho/para converters (M. Snow, 6-16-01)

There are two ortho-para converters in the target system. One is on the gas handling system and operates at 77K. The other is on the cold stage of the cryorefrigerator and doubles as the liquefaction region. Both use chromic oxide (CrO_3) as the active converter material. Our choice of CrO_3 is based on the data of N. S. Sullivan et al, which showed that CrO_3 is a more effective catalyst than the more commonly-used iron oxide.

- **specifications (M. Snow, 6-16-01)**

Both converters will be enclosed in OFHC copper chambers with fine mesh to prevent converter material from reaching other regions. Both converters will be bakeable for reactivation. Table 5 lists the important properties of the two ortho-para converters which are different.

Table 5: Ortho-para converter data

Ortho-Para Converter	Geometric and Thermodynamic Data			Geometry and Cooling
	Volume	Rate of Heat Removal	Operating Temperature and O/P Ratio	
Gas Handling System	500 cc		77K->50%	Gas inlet and outlet. Liquid Nitrogen
Main Vacuum vent line	280 cc		17K->99.95% para	Gas inlet, liquid condensed on top surface, drips into annular converter. Cryorefrigerator.

- **design (M. Snow, 4-11-01)**

The ortho-para converter chamber which is operated on the 17K cold head of the cryorefrigerator doubles as the liquid condensation chamber. The gas is liquefied at the top of the chamber by thermal contact with a grooved OFHC copper surface. The liquid drips down into the converter. The geometry of the converter is arranged in the form of an annular cup. Liquid enters a central tube and flows into the converter from below through holes in the tube. The liquid level rises gradually, spending a long time in contact with the converter. At the top of the cup the liquid spills over the edge and flows out radially into another annulus which leads down into a tube at the bottom which fills the target. The body of the converter is made of copper to allow the converter material to be heated for regeneration if necessary. The CrO_3 is prevented from leaving the annular region with fine wire mesh on the inlet and outlet. The body of the converter is designed as a two-piece device to allow for the replacement of the converter if required.

- **data sheets**
- **test results**

Cryocoolers

- **specifications (M. Snow, 5-26-01)**

The cryorefrigerators will both be two stage closed-cycle mechanical refrigerators based on the Gifford McMahon cycle. The operation of the refrigerators is independent of their spatial orientation. The refrigerator for the hydrogen gas will be oriented vertically and the refrigerator for the radiation shields will be oriented upside-down along the same axis. Both refrigerators contain moving parts which must be made of nonmagnetic materials (nonmagnetic stainless is sufficient) so that the magnetic field in the experiment can be made with sufficient uniformity. Table 6 lists the relevant properties of the two cooling stages.

Table 6: Properties of the two-stage cryorefrigerators

Cooling Stage	Thermodynamic Data			Mechanical Data
	Cooling Power	Temperature Stability, no load	Operating Range	Frequency
Stage 1, 77K	60 W	0.5K	77K->300K	1.2 Hz
Stage 2, 20K	12 W	0.5K	11K->300K	1.2 Hz

- **cryostat design calculations (M. Snow, 4-10-01)**

Let us recall some of the basic facts about the properties of liquid hydrogen and its thermodynamics:

density: 0.071 g/cc
latent heat of vaporization: 444J/g
heat of ortho-para conversion: 709 J/g
specific heat of H2 gas: approx: 12 J/gK from 20-300K

The LH2 volume of the target is 21 liters. This gives a target mass of 1.5 kg and corresponds to a total gas volume at room temperature and 1 bar pressure of 18 cubic meters. For this volume, 4300 kJ is required to cool the gas from 300K to 80K, 950 kJ is required to cool the gas from 80K to 20K, 665 kJ is required to liquify the gas at 20K, 40 kJ is required to cool the liquid from 20K to 17K, and 1070 kJ is required to convert the gas to parahydrogen, with about a third of the heat of conversion released by 80K. If we neglect the effect of the ortho-para conversion in the gas handling system and assume that all ortho-para conversion occurs in the condenser, then the 80K stage of the cryorefrigerator must remove 4835 kJ and the 17K stage must remove 2190 J. Given the cooling power of one cryorefrigerator (60 watts at 80K, 12 watts at 20K) and the radiative heat load on the 80K and 17K radiation shields (15 watts and 0.1 watts, respectively), then the liquification of the target takes 2 days, with the rate set by the cooling power of the 17K cooling stage. This corresponds to a gas flow rate in the gas handling system of about 10 standard liters/minute.

The radiative heat loads on the radiation shields quoted above are calculated using the usual Stefan-Boltzmann law asuming a geometry of concentric cylinders, an emissivity of 0.02, and temperatures for the radiating surfaces of 300K, 150K, and 17K. The second cryorefrigerator will easily be able to remove the 0.1 watt heat load on the inner radiation shield.

The radiation shields and the thermal connection to the target chamber will be made of OFHC copper. Given the thermal conductivity of copper (20 W/cm*K at 20K), one can estimate the required cross sectional area of the thermal connection to the target as follows. For the liquid target, assume that the refrigerator is operated at a temperature two degrees lower (15K) than the target temperature (17K). (This is safely above the solidification temperature of liquid hydrogen at a pressure of 1/3 bar of 14 K). Furthermore, assume that one requires a cooling power 5 times the expected radiative heat load on the target without the operation of the second refrigerator, or 0.5 W. (In fact, with the operation of the second cryorefrigerator cooling the radiation shield to a temperature below 17K, the dominant heat load on the target is due to the thermal conductance of the liquid hydrogen itself in contact with the warmer vapor in the exhaust line and the thermal conductance of the exhaust line tubing. Given the small conductivities involved [liquid H2: 1.2 mW/cm*K, gaseous H2: 0.15 mW/cm*K, stainless steel in the exhaust line: 10 mW/cm*K], the expected heat load from this source is on the order of tens of mW. Heat due the the neutron beam capture and gamma loss in the taregt is at the few microwatt level) Then the required ratio of area to length for the thermal connection in this extreme case is

(area/length)=0.5W/([20W/cm*K]*2K)=0.0125 cm

For a length of 20 cm for the thermal connection between the refrigerator and target, this gives a cross sectional area of 0.25 square cm. This cross sectional area can easily be supplied using copper braid.

- **data sheets (M. Snow)**

The Appendix includes a plot of the cooling power of the two stages of the CVI CGR511 refrigerator which will be used to liquefy and convert the hydrogen.

- **test results**

LH2 Target Instrumentation

The instrumentation required for the operation of the liquid hydrogen target can be divided into systems internal to and external to the main vacuum system. Inside the vacuum system, the instrumentation consists of three main components: (1) thermometry, (2) pressure gauges, and (3) a LH2 liquid level meter. Outside the system, the instrumentation consists of gas sensors inside the cave to detect hydrogen.

- **LH2 target instrumentation (M. Snow, 4-22-01)**

Table 7 lists the in-vacuum instrumentation and its technical requirements.

Table 7: Instrumentation associated with target operation.

Instrument	Transducer Requirements			Mechanical Data
	Locations	Operating Range	Accuracy	Reproducibility
Thermometers	LH2 target, O/P converter, cryorefrigerator stages, radiation shields, target outlet. No thermometers inside LH2 chamber	10-300K on target, second stage of refrigerators, O/P converter, cold radiation shield. 70-300K on warm radiation shield, first stage of refrigerators	0.2K accuracy in 10-30K range, 2K accuracy in 70-300K range	0.1K in 10-30K range, 2K in 70-300K range
Pressure Gauges	LH2 target, main vacuum, He jacket. All located on GHP external to cave	2->10E-7 bar on main vacuum and LH2 target. 2->10E-3 bar on He jacket	11K->300K	3% near atmospheric pressure
Heaters	LH2 target, O/P converter, cryorefrigerator stage 2, target outlet at liquid-vapor phase boundary.	0-several watts		
LH2 level meter	Inside LH2 target	empty->full	11K->300K	

- **specifications**
- **design (M. Snow, 4-22-01)**

The pressure gauges and thermometers are commercially-available components. The liquid level meter will consist of a string of carbon resistors immersed in the liquid with a current source and a DC voltmeter. The gauge will exploit the change of resistance experienced by a carbon thermometer upon immersion in liquid hydrogen. This type of level gauge has been described in the paper on the HARP liquid hydrogen target in the references.

- **test results**

- **hydrogen detectors**
  - **specifications**
  - **design**
  - **data sheets**
  - **test results**

System Operation and Safety Controls (M. Snow, 5-6-01)

We will provide the target system with a detailed operating procedure in a future safety review. A preliminary operating procedure for filling the LH2 target is presented in

Appendix 4. For this report we restrict ourselves to an outline of our proposed control system.

We propose to provide an Allen-Bradley Programmable Logic Controller (PLC) for operation of the target. The PLC performs the monitoring, controls, and communications with all of the transducers for the target. The control software provides an operator with a computer interface with real-time control and data acquisition in both text and graphical format. All parts of the system will be depicted with animation that can display graphically all signals, both in real-time mode and in a historical mode. An information page of the status of the system will be created for network communications to be sent both to the NPDG DAQ and to the LANSCE CCR.

We furthermore propose a separate safety control system. This system would be concerned with the monitoring of only those transducer signals which are associated with target safety. It would monitor safety-sensitive signals and operate devices such as fans associated with hydrogen safety. It would be interlocked in an appropriate manner with the LANSCE safety systems.

- **specifications**
- **design**
- **data sheets**
- **test results**

Cave hydrogen safety

- **Electricity (H. Nann, 5-1-01)**

The whole point of the safety design is to allow for the possibility to use ordinary equipment in the experimental cave by preventing hydrogen from entering the cave in the first place. We argue that therefore we do not need explosion-proof electronics. The robust design of the flask and vacuum jacket plus the addition of the helium jacket makes release of hydrogen into the cave extremely unlikely.

- **Ventilation**
- § **design and specifications (H. Nann, 6-10-01)**

We intend to design the ventilation as needed for personnel comfort and the needs of the experiment. This air flow is not a primary part of the hydrogen safety system since the hydrogen is considered to be adequately contained by the robust hydrogen flask, vacuum vessel, and helium jacket.

The exhaust port will be located near ceiling of cave in a location which allows for the best neutron shielding. Ventilation rate: 6,000 l/min (200 cfm) (this means that we change air in the cave every 10 min.)

Fan motor either explosion-proof or mounted outside air stream. Rotor to be non-sparking construction. Exhaust ducted outside building

  - § **data sheets**

- **testing**
- **H2 sensors**
  - **specifications**
  - **design**
  - **data sheet**
  - **test results**

Radiological safety (H. Nann, 5-20-01)

The exposure of various items of the experiment to the neutron beam for a time of approximately one year will cause activation of certain components. Almost all of this activation will be prompt gammas from cold neutron capture. However, there are a couple of sources of tritium generation in the experiment. Here we make estimates of the amont of tritium generated in the hydrogen target due to (A) interactions with 3He impurities in the 4He jacket, (B) interactions with deuterium in the LH2 target.

(A) ^{3}He(n,p)^{3}H

(n,p) cross section at E_n = 1 keV: σ(1 keV) = 27 b

Assume $\sigma \propto 1/v$ dependence $\Rightarrow$ σ(4 meV) = 1.35×10^4 b = 1.35×10^{-20} cm^2

Natural abundance of ^{3}He: 1.37×10^{-6}

At STP: 22.4 L of helium contain 6.02×10^{23} atoms

1 cm^3 at 1.2 atm contains 3.22×10^{19} atoms

_ 1 cm^3 of natural He at 1.2 atm contain 4.41×10^{13} atoms of ^{3}He.

Assume a target thickness of 1 cm $\Rightarrow$ d(3He) = 4.41×10^{13} atoms/cm^2

Neutron flux: $\Phi = 1 \times 10^{10}$ neutrons/sec

Luminosity: $L = \Phi \cdot d = 4.41 \times 10^{23}\ s^{-1}\ cm^{-2}$

Tritium yield: $Y = L \cdot \sigma = 5954\ s^{-1} = 1.88 \times 10^{11}$ per year

Activity: $A = \lambda \cdot N$

Half-life of tritium: $t_{1/2}$ = 12.33 yr = 3.89×10^8 s

$$\lambda = \frac{\ln 2}{t_{1/2}} = 1.78 \times 10^{-9}\ s^{-1}$$

_ $A = (1.78 \times 10^{-9}\ s^{-1})(1.88 \times 10^{11}) = 335\ s^{-1}$

(A) ^{2}H(n,γ)^{3}H

(n,γ) cross section at 25 meV: σ(25 meV) = 5.2 mb

Assume $\sigma \propto 1/v$ dependence $\Rightarrow$ σ(4 meV) = 13 mb = 1.3×10^{-26} cm^2

Natural abundance of ^{2}H: 1.48×10^{-4}

20 L of LH_2 density of LH_2: $\rho = 66$ kg/m^3
mass of LH_2: $m = \rho V = (66\ \text{kg/m}^3)\ (20 \times 10^{-3}\ \text{m}^3) = 1.320\ \text{kg} = 1320\ \text{g}$

molecular mass of H_2: M = 2.016 g/mol

number of moles: $n = m/M = (1320\ \text{g})/(2.016\ \text{g/mol}) = 655\ \text{mol}$

number of atoms: $N = n\,N_A = (655\ \text{mol})(6.02 \times 10^{23}\ \text{mol}^{-1}) = 3.94 \times 10^{26}$

_ 20 L of LH_2 contain 5.83×10^{22} deuterium nuclei. They are distributed over a circular area of 30 cm diameter.

_ $d(^2H) = 8.25 \times 10^{19}$ nuclei/cm^2

Neutron flux: $\Phi = 1 \times 10^{10}$ neutrons/sec

Luminosity: $L = \Phi \cdot d = 8.25 \times 10^{29}\ \text{s}^{-1}\ \text{cm}^{-2}$

Tritium yield: $Y = L \cdot \sigma = 1.07 \times 10^{4}\ \text{s}^{-1} = 2.78 \times 10^{10}$ per month

Activity: $A = \lambda \cdot N$

$A = (1.78 \times 10^{-9}\ \text{s}^{-1})(2.78 \times 10^{10}) = 50\ \text{s}^{-1}$

Warnings, Alarms, and Interlocks (J. Novak, H. Nann, 6-22-01)

We propose a three-tiered hierarchy of status indicators for the system as follows:

Normal: The system operating as designed with all interlocks and sensors active and within set ranges.
Warning: Some sensor(s) are at values between low and high trip points. Local indication (horn, lights, signs) and possibly phone dialer initiated. Operator attention is required but automatic shutdown action is not needed. Necessary personnel may be near the equipment with caution; others should stay away.
Alarm: Some sensor(s) have exceeded their high trip levels. Automatic safety and/or shutdown systems take over. Local indications (horns, lights, signs). All personnel should leave the area. Neutron beam in experiment flight path shut off. CCR automatically notified. Phone dialer initiated.

Sensor	**Location**	**Trip point**	**Action**

H_2 concentration #1 H_2 concentration #2	Cave, in stagnant air near ceiling	10% of LEL	Warning
H_2 concentration #1 H_2 concentration #2	Cave, in stagnant air near ceiling	25% of LEL	Alarm. H_2 System shutdown and rapid H_2 dump. Electrical power in cave shut off.
Air flow	Cave exhaust	70% of normal flow	Warning
Vacuum (pressure) sensor	Vacuum vessel	Bad	Warning
H_2 concentration	Vacuum vessel	Low	Warning
H_2 concentration	Vacuum vessel	High	Alarm. H_2 System shutdown and rapid H_2 dump.
RGA	Vacuum vessel	He peak > Low	Warning
RGA	Vacuum vessel	He peak > High	Alarm. H_2 System shutdown and rapid H_2 dump.
RGA	Vacuum vessel	N_2 peak > Low	Warning
RGA	Vacuum vessel	H_2O peak > Low	Warning
He pressure	Helium jacket	p < 3 psig	Warning
H_2 pressure	Target gas in condenser unit	p > 11 psig, p < 9 psig	Warning
O_2 concentration #1 O_2 concentration #2	Cave, at normal breathing space elevation	Low	Warning

- **signals connected to facility**

- **local status signals**

Failure analysis

- **Risk management**
  - **Plan**
  - **Failure analysis (J. Novak, H. Nann, 6-22-01)**

    The following series of tables constitutes an assessment of the failure modes for the liquid hydrogen target system and an analysis of how our proposed design deals with each failure mode.

<u>**NPDGamma LIQUID HYDROGEN TARGET**</u>
<u>**POSSIBLE FAILURES RELATED TO HYDROGEN SAFETY**</u>
Update of J. Novak's original version by H. Nann.

NOTES

LIKELIHOOD LEVEL ABBREVIATIONS:

5 Frequent ("Happened to you many times.") (Expected once in 1-10 tries)
4 Probable ("Happened to you once.") (Expected once in 10-100 tries)
3 Occasional ("Was a near-miss to you.") (Expected once in 10^2-10^4 tries)
2 Improbable ("Happened once to someone you know") (Expected once in 10^4-10^6 tries)
1 Remote ("Happened once, long ago, at another facility").(Expected once in 10^6-10^8 tries)

SEVERITY LEVEL ABBREVIATIONS

Note: Some scale of severity related to equipment damage is needed.

4 Catastrophic (Death, coma, loss of limb, loss of sight) (Closing TA-53)
3 Critical (Broken bones, bad cuts, 3rd degree burns, unconsciousness, out of work 1 week to 1 month) (Major stand down)
2 Moderate (2nd degree burns, out of work 1 day to 1 week, work restrictions up to 1 week) (Incident reportable to DOE headquarters, $50,000 loss)
1 Negligible (No lost work days, work restrictions up to 1 day) (______________)

IS = Initial Severity
IL = Initial Likelihood
RS = Residual Severity
RL = Residual Likelihood

A	COMPONENT RUPTURES

1	**System**	LH_2
	Component	Target flask or piping inside vacuum vessel
	Failure	Rupture — due to material or weld failure

	Result	LH_2 release to vacuum vessel. Rapid pressure rise in vacuum vessel and flask. Possible overpressure rupture of vacuum vessel.		
	Initial Severity	**1** If no vacuum vessel or relief failures	**Initial Likelihood**	**2**
	Failure Mitigation	***Design to ASME code.*** ***Use certified materials.*** ***Use certified welders.*** Radiograph welds. Pressure test final assembly. Vacuum vessel is secondary container. Design it and its relief system to handle full rupture of LH_2 flask.		
	Residual Severity	**1**	**Residual Likelihood**	**1**
2	**System**	LH_2		
	Component	Target flask or piping inside vacuum vessel		
	Failure	Rupture — due to overpressure (inadequate relief capacity)		
	Result	LH_2 released to vacuum vessel. Rapid pressure rise in vacuum vessel. Possible overpressure rupture of vacuum vessel		
	Initial Severity	**1** If no vacuum vessel or relief failures	**Initial Likelihood**	**2**
	Failure Mitigation	***See Item A.1.*** Design LH_2 vent lines and relief valve capacity carefully for max. credible heat load. ***Design to ASME code.*** Design using highest pressure and thickest materials consistent with physics goals. ***Use redundant relief valves.*** ***Vacuum vessel is secondary container. Design it and its relief system to handle full rupture of LH_2 flask.*** Pressure test final assembly.		
	Residual Severity	**1**	**Residual Likelihood**	**1**
3	**System**	Vacuum jacket		
	Component	Main vacuum vessel, vacuum piping		
	Failure	Rupture — due to material or weld failure		

Result	He or air, depending on location of break, floods vacuum space; high heat load on LH_2 flask. If H_2 vessel ruptures, have air/H_2 mixture in vacuum space; see Contaminants Section		
Initial Severity	**1** if LH_2 system does not rupture. See Item A.2 **3 or 4** if H_2/air mixture in vacuum space. **4** if LH_2 flask and helium jacket rupture	**Initial Likelihood**	**2**
Failure Mitigation	***See Items A.2, C.1.*** ***Design to ASME code.*** ***Use certified materials.*** ***Use certified welders.*** ***Radiograph welds*** ***Surround vacuum jacket and piping inside cave with helium jacket so that vacuum space will be filled with helium, not air.*** ***For piping that is difficult to enclose in helium jacket, build from very strong, reliable components (e.g., all welded components, VCR fittings, etc.).*** *Pressure test final assembly.*		
Residual Severity	**1**	**Residual Likelihood**	**1**

4	**System**	Vacuum jacket		
	Component	Main vacuum vessel, vacuum piping		
	Failure	Rupture — due to *external* pressure (from helium jacket)		
	Result	He floods insulating space; high heat load on LH_2 flask.		
	Initial Severity	**1** if LH_2 system does not rupture. See Item A.2 **4** if LH_2 flask and helium jacket rupture	**Initial Likelihood**	**2**
	Failure Mitigation	***See Item A.3.*** ***Design to ASME code.*** Design for appropriate external pressure. Design helium jacket pressure control and relief system appropriately to avoid high external pressures.		
	Residual Severity	**1**	**Residual Likelihood**	**1**

5	**System**	Vacuum jacket
	Component	Main vacuum vessel and piping

Failure	Rupture — due to *internal* pressure (e.g., when LH_2 flask ruptures)		
Result	LH_2 release to helium jacket. Rapid pressure rise in helium jacket and LH_2 flask, with possible overpressure rupture		
Initial Severity	**1** if helium jacket or vacuum piping do not rupture **4** if helium jacket ruptures	**Initial Likelihood**	**2**
Failure Mitigation	***See Items A.1, A.2.*** Design vacuum vessel vent line and relief valve capacity carefully for max. credible gas evolution rate. ***Design to ASME code.*** Design using highest pressure and thickest materials consistent with physics goals. Design for appropriate internal pressure. ***Use redundant relief valves.*** Design helium jacket relief system appropriately		
Residual Severity	**1**	**Residual Likelihood**	**1**

B	**COMPONENT FAILURES**

1

System	Refrigerator		
Component	Any		
Failure	Cooling failure (either device or power failure)		
Result	H_2 pressure rises slowly. Heat load is much lower than maximum credible failure. Relief valves open. No safety problems, only operational problems.		
Initial Severity	**1**	**Initial Likelihood**	**4**
Failure Mitigation	Redundant refrigerators or auxiliary generator, if importance to experiment operation justifies the cost.		
Residual Severity	**1**	**Residual Likelihood**	**1**

2

System	Refrigerator
Component	Temperature controller
Failure	Fails low

	Result	LH_2 freezes. Possible line plugging with frozen hydrogen. Possible reduction of H_2 gas pressure below atmospheric, with increased risk of drawing in air/contaminants.		
	Initial Severity	**1**	**Initial Likelihood**	**3**
	Failure Mitigation	Interlock target pressure and temperature sensors to alarm and possibly to refrigerator shutoff. Surround H_2 system inside cave with helium jacket.		
	Residual Severity	**1**	**Residual Likelihood**	**1**
3	**System**	Refrigerator		
	Component	Temperature controller		
	Failure	Fails high		
	Result	Inadequate cooling. If refrigerator is ON, gives extra heat load on LH_2 system. If refrigerator is OFF, could cause very hot local spot in piping , possibly weakening piping, damaging heater, or causing electrical short to ground.		
	Initial Severity	**1**	**Initial Likelihood**	**4**
	Failure Mitigation	Interlock temperature controller to refrigerator operation and/or flask temperature.		
	Residual Severity	**1**	**Residual Likelihood**	**1**
4	**System**	Vacuum jacket		
	Component	Relief valve(s)		
	Failure	Fails to open or opens only partially		
	Result	High pressure in vacuum jacket. Possible rupture. H_2 release to helium jacket (if vacuum jacket ruptures) or to air (if vacuum piping or pumping system rupture), if gas source is LH_2 flask failure. Rapid pressure rise in helium jacket, with possible overpressure rupture		
	Initial Severity	**1** if helium jacket or vacuum piping do not rupture **4** if H_2 is released to cave **3** if H_2 is released outside cave	**Initial Likelihood**	**2**

	Failure Mitigation	Use ASME code relief valves or devices with equal reliability. Use redundant relief valves. Design helium jacket relief system appropriately for vacuum jacket rupture		
	Residual Severity	**1**	**Residual Likelihood**	**1**
5	**System**	LH_2 flask		
	Component	Relief valve(s)		
	Failure	Fails to open or opens only partially		
	Result	High pressure in LH_2 flask. Possible rupture. LH_2 release to vacuum jacket Rapid pressure rise in vacuum jacket, with possible overpressure rupture		
	Initial Severity	**1** if vacuum jacket or vacuum piping do not rupture **4** if H_2 is released to cave **3** if H_2 is released outside cave	**Initial Likelihood**	**2**
	Failure Mitigation	Use ASME code relief valves or devices with equal reliability. Use redundant relief valves. Design vacuum jacket relief system appropriately for H_2 flask rupture		
	Residual Severity	**1**	**Residual Likelihood**	**1**
6	**System**	Helium jacket		
	Component	Relief valve(s)		
	Failure	Fails to open or opens only partially		
	Result	High pressure in helium jacket. Possible rupture. Possible damage to or collapse of vacuum jacket if source of gas is He supply failure. H_2 release to cave air if He jacket ruptures and gas source is LH_2 flask failure. He released to cave air if source is He supply gas failure.		
	Initial Severity	**1** if helium jacket does not rupture **4** if H_2 is released to cave **2** if He is released to cave	**Initial Likelihood**	**2**
	Failure Mitigation	Use ASME code relief valves or devices with equal reliability. Use redundant relief valves. Design helium jacket relief system appropriately for vacuum jacket rupture or He supply system failure.		
	Residual Severity	**1**	**Residual Likelihood**	**1**

7	**System**	Vacuum jacket		
	Component	Vessel or piping		
	Failure	Damage/rupture from shrapnel created by rupture of the LH_2 flask		
	Result	See items on rupture of vacuum jacket from other causes. LH_2 released to cave IF helium jacket also ruptures		
	Initial Severity	**1** if helium jacket stays intact. **4** if helium jacket ruptures	**Initial Likelihood**	2
	Failure Mitigation	Use ductile materials for all vessels at all temperatures. *Design to ASME code.*		
	Residual Severity	**1**	**Residual Likelihood**	1

8	**System**	Helium jacket		
	Component	Vessel or piping		
	Failure	Damage/rupture from shrapnel created by rupture of the vessel inside		
	Result	LH_2 release to cave See Items on rupture of vacuum jacket from other causes.		
	Initial Severity	4	**Initial Likelihood**	2
	Failure Mitigation	Use ductile materials for all vessels at all temperatures. *Design to ASME code.*		
	Residual Severity	**1**	**Residual Likelihood**	1

9	**System**	H_2 gas handling system		
	Component	Pipes outside cave		
	Failure	Broken or leaking		
	Result	H_2 release into ER2		
	Initial Severity	**1** if leaking **2** if broken	**Initial Likelihood**	2
	Failure Mitigation	Build from very strong, reliable components (e.g., all welded components, VCR fittings, etc.). Protect all pipes from mechanical damage.		

	Residual Severity	**1**	**Residual Likelihood**	**1**

C	**CONTAMINANTS**			
1	**System**	LH_2		
	Component	Target flask or piping inside the vacuum jacket.		
	Failure	Plugged vent line -- due to freezing of contaminants		
	Result	Rupture — due to overpressure LH_2 release to vacuum vessel. Rapid pressure rise in vacuum vessel. Possible overpressure rupture of vacuum vessel.		
	Initial Severity	**1** If no vacuum vessel or relief failures and redundant relief line is open.	**Initial Likelihood**	**4**
	Failure Mitigation	***See item A.2.*** Use redundant vent paths. Use certified feed gas and input gas cleanup. Helium jacket all H_2 lines inside cave. Weld all joints and use high reliability components on all H_2 lines where He jacket is impractical. Have thorough leak check procedures. Have thorough procedures to remove contaminants from H_2 system before cool-down. Helium purge on discharge side of all relief devices.		
	Residual Severity	**1**	**Residual Likelihood**	**1**
2	**System**	Vacuum jacket		
	Component	All		
	Failure	Air leak — large or small (due to any cause, but probably to leakage of vacuum piping outside the He jacket or to operator error).		
	Result	High heat load on LH_2 flask if large air leak. Low heat load on LH_2 flask if small air leak. Possible air/H_2 mixture in vacuum vessel if flask ruptures		
	Initial Severity	**1** if LH_2 system does not rupture. See Item A.2 **3 or 4** if H_2/air mixture in vacuum space.	**Initial Likelihood**	**2**

Failure Mitigation	***See Items A.2, A.3, A.4, C.1, E.2*** ***Design to ASME code.*** ***Surround vacuum jacket and piping with helium jacket so that vacuum space will be filled with helium, not air.*** Pressure test final assembly.		
Residual Severity	**1**	**Residual Likelihood**	**1**

3	**System**	Vacuum jacket		
	Component	All		
	Failure	Helium leak — large or small		
	Result	See items on vacuum jacket failure, A.3, A.4 Large leak -- He floods insulating space; high heat load on LH_2 flask. Small leak -- He invades insulating space; moderate heat load on LH_2 flask.		
	Initial Severity	**1** if LH_2 system does not rupture. See Item A.2 **4** if LH_2 flask and helium jacket rupture	**Initial Likelihood**	**2**
	Failure Mitigation	Design and build LH_2 flask, piping, and relief system appropriately.		
	Residual Severity	**1**	**Residual Likelihood**	**1**

4	**System**	H_2 gas handling system		
	Component	All		
	Failure	Air leaks — small or large		
	Result	Air/H_2 mixture inside H_2 system. Plugs in piping to cold regions. See item C.1 Result for small and large leaks is same, except that everything happens faster for large leaks and there is greater potential for combustible H_2/O_2 mixtures.		
	Initial Severity	**1** IF no vacuum vessel or relief failures and redundant relief line is open. **2 to 3** if combustible mixture is formed.	**Initial Likelihood**	**2**
	Failure Mitigation	***See item A.2, C.1*** Use redundant vent paths. Leak check all joints and components carefully at assembly. Weld all joints and use high reliability components on all H_2 lines. Helium purge on discharge side of all relief devices. Do periodic leak check procedures.		

Residual Severity 1 **Residual Likelihood** 1

D FIRES, NATURAL EVENTS

1 **System** ER2

Component General area of target system

Failure Fire

Result Increased fire severity if H_2 gas is released

Initial Severity 2 **Initial Likelihood** 1

Failure Mitigation
Building sprinkler system.
Good housekeeping.
Local fire extinguishers
Initiate LH_2 Òfast emptyÓ system

Residual Severity 1 **Residual Likelihood** 1

2 **System** H_2 vent line

Component

Failure Fire at exit of vent line

Result Possible combustion into vent pipe if air/H_2 mixture exists. Possible ignition of materials near vent exit.

Initial Severity 2 **Initial Likelihood** 2

Failure Mitigation
Put vent line check valve close to exit to minimize length/volume of air/H_2 mixture.
Purge line between relief valves and check valve with helium.
Locate vent stack in safe area.

Residual Severity 1 **Residual Likelihood** 1

3 **System** Electrical power

Component All

Failure Interruption

Result	Possible unintended valve operation. Loss of refrigeration. Loss of system status indication. Loss of cave ventilation		
Initial Severity	**2**	**Initial Likelihood**	**5**
Failure Mitigation	Use Power-To-Open valves where appropriate. Use Power-To-Close valves where appropriate. Use mechanical gages as appropriate. All personnel out of cave during power outage.		
Residual Severity	**1**	**Residual Likelihood**	**5**

E OPERATIONAL ERRORS

1	**System**	Vacuum		
	Component	Valve		
	Failure	Operator opens with vacuum pump not running and H_2 system cold.		
	Result	Large flood of air into vacuum space, large heat load on LH_2 system. See A.3, etc.		
	Initial Severity	**1** if no LH_2 system or relief failures	**Initial Likelihood**	**4**
	Failure Mitigation	Interlock valve operation with refrigerator. Close valve when LH_2 system is cold.		
	Residual Severity	**1**	**Residual Likelihood**	**1**

2	**System**	H_2 gas, vacuum, helium, refrigerator, etc. -- CONTROLS		
	Component	All		
	Failure	(Under analysis at this writing)		
	Result	(Under analysis at this writing)		
	Initial Severity	?	**Initial Likelihood**	**?**
	Failure Mitigation	?		
	Residual Severity	**1**	**Residual Likelihood**	**?**

Drawings

Hydrogen Safety Committee Reports

Reference list (H. Nann, M. Snow, 6-25-01)

The following references were consulted in the course of the preparation of this report:

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Hydrogen Vent Systems, Compressed Gas Association, CGA G-5.5, Arlington, VA (1996).

Pressure Relief Device Standards, Part 3-Compressed Gas Storage Containers, S-1.3 Compressed Gas Association, Arlington, VA (1995).

ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and 2

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M. Wiseman et al., Applications of Cryogenic Technology, Vol. 10, Edited by J.P. Kelley, Plenum Press, New York, 287 (1991)

D. H. Weitzel et al, Elastomers For Static Seals at Cryogenic Temperatures, Advances in Cryogenic Engineering 6, 219 (1961).

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M. Hoenig, Advances in Cryogenic Engineering 14, Plenum Press, New York, 627 (1972).

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Appendices

Appendix 1 (J. Novak, H. Nann, 6-20-01): A condensed summary of the main features of the proposed operating parameters for the target and its safety features and tests. Update of J. Novak's original proposal by H. Nann.

REQUIREMETS --

1. Target has to be safe to operate in any conditions and it has to handle any abnormal conditions.
2. Target has to meet any laboratory safety requirements
3. Entry to the experimental cave is required when the target is full.
4. For physics;
   - ≤ 10% neutrons can be lost in the entry walls.
   - ≤ 10% gamma rays from neutron capture on proton can be lost on the walls.

GIVEN --

LH_2 FLASK

1. 30 cm diam. x 30 cm long
2. Volume: 20 liters
3. Material: 5083-O alloy aluminum with AZ31C-H24 magnesium alloy entrance window.
4. Dished ends (concave)
5. Thin windows not needed because beam is low energy neutrons
6. ^{6}Li-loaded liner to absorb stray neutrons inside the flask
7. LH_2 in target region needs to be sub-cooled to minimize bubbles and maximize para- fraction. Normal operating pressure (the pressure of the gas phase) is *proposed* to be 10.2 psia, so the liquid at the liquid/gas interface will be saturated at this pressure. The target region will be cooled about 2K below this interface temperature.

DETECTORS

Have to cover as much solid angle as possible. The detectors together with electronics (48 detectors and electronic channels) are expensive, therefore, need to be close to the target to minimize costs. Thus, small distance between flask walls and detector crystals is desirable. At present, 48 CsI crystals are defining the max diameter of the target cryostat.

EXPERIMENTAL CAVE

1. Walls and roof will be a combination of steel and poly and most probably boronated wax, no cave design before MCNP shielding calculations. The total

thickness of the walls will be about 12-16 inch.

2. “Neutron gas” inside cave makes even small penetrations in the cave walls difficult to shield.
3. Dimensions inside approx. 4m x 5m x3m high = 60 cu. meters
4. Need personnel access while target is running.
5. Will have energized electrical devices inside with hydrogen ignition potential.

PROPOSED –

The LH_2 target system consists of three components: a target flask containing the liquid hydrogen, an insulating vacuum vessel, and a helium jacket surrounding the vacuum vessel. All components were designed according to the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and 2; ASME B31.3 Code for Pressure Piping – Process Piping; CGA S-1.3 Pressure Relief Device Standards – Part 3 – Stationary Storage Containers for Compressed Gases (referred to as CODE). Each component is equipped with a primary relief system of a spring-loaded pressure relief valve and a parallel, secondary relief system of a rupture disc. All pressure reliefs are connected to a large size (6 inch diameter 304L stainless steel pipe) vent line, which is filled with nitrogen at atmospheric pressure, to the outside of the building.

1. LH_2 Flask:

Material: 5083-O aluminum except for AZ31C-H24 magnesium alloy entrance window; wall thickness 0.10 inch

A) Design pressure (calculated according to CODE formulae): internal: 160 psia (10.2 atm) - external (0.6 times internal): 96 psia (6.5 atm)

B) Normal operating pressure: 10.2 psia (0.7 atm); the atmospheric pressure at Los Alamos is 11.2 psia.

C) Maximum allowable working pressure (internal): 70 psig (4.8 atm)

D) Relief paths: single 1.5-inch I.D. piping up to pressure relief valve and rupture disk

E) Relief valve flow capacity: 0.20 lb/s

F) Pressure relief valve set point: 7 psig

G) Rupture disk set point: 75 psig

1. Insulating Vacuum Vessel:

Material: 5083-O aluminum except for unalloyed titanium entrance window; wall thickness 0.10 inch

A) Design pressure (calculated according to CODE formulae): internal 150 psia (10.2 atm) - external (0.6 times internal): 90 psia (6.1 atm)

B) Normal operating pressure: vacuum

C) Maximum allowable working pressure (internal): 70 psig (4.8 atm)

D) Relief paths: single 2.5-inch I.D. piping up to pressure relief valve and rupture disk

E) Relief valve flow capacity: 0.50 lb/s

F) Pressure relief valve set point: 20 psig

G) Rupture disk set point: 75 psig

1. Helium Jacket:

Material: 5083-O aluminum except for unalloyed titanium entrance window; wall thickness 0.10 inch

A) Design pressure (calculated according to CODE formulae): internal 150 psia (10.2 atm) - external (0.6 times internal): 90 psia

B) Normal operating pressure: 18 psia (1.2 atm)

C) Maximum allowable working pressure (internal): 70 psig (4.8 atm)

D) Relief paths: single 0.75-inch I.D. piping up to pressure relief valve and rupture disk

E) Relief valve flow capacity: 0.05 lb/s

F) Pressure relief valve set point: 25 psig

G) Rupture disk set point: 75 psig

TARGET SYSTEM TESTS

These tests will be performed at IUCF

1. Test each component hydrostatically up to 100 psig. The calculated internal design pressure for the target flask is 160 psia and for the vacuum vessel 150 psia.

2. Test of overpressure behavior and sizing of the safety relief devices of the LH_2 target system by controlled spoiling of the insulating vacuum with air. (A similar test has been performed at JLAB with their cryomodules: M. Wiseman et al., Applications of Cryogenic Technology, Vol. 10, Edited by J.P. Kelley, Plenum Press, New York, 1991).

〈 Pressure relief valve is set at 7 psig (= 21.7 psia at Bloomington, IN) and rupture disc at 75 psig.
〈 Instrument target flask, buffer volume, and exhaust line just upstream of relief devices with pressure and temperature transducers and recorders.
〈 Fill target flask with LN_2 at atmospheric pressure.
〈 Bleed air into insulating vacuum through calibrated needle valve to control flow rate.
〈 From pressure and temperature response versus time determine maximum N_2 mass flow rate through relief valve and piping system.
〈 Calculate maximum H_2 mass flow rate using latent heat of evaporation for N_2 (160 kJ/L) and H_2 (31.8 kJ/L).

1. Test overpressure behavior and sizing of the safety relief devices of the vacuum vessel by suddenly dumping 20 L of LN_2 into it.

〈 Pressure relief valve is set at 20 psig and rupture disc at 75 psig.
〈 Instrument vacuum vessel with pressure transducers and recorders.
〈 Replace magnesium entrance dome of the target flask with a similar size aluminum plate that has a thin Mylar window.
〈 Fill the target flask with LN_2 at atmospheric pressure.
〈 Rupture the Mylar window with a motorized knife.
〈 Record pressure versus time.

GAS MONITORING

1. Monitor vacuum space for hydrogen, helium, nitrogen, and oxygen with RGA.

2. There is no need to monitor the helium jacket for hydrogen. Hydrogen will be detected in the vacuum long before it is seen in the helium jacket.

CAVE EXHAUST

1. As needed for personnel comfort. This air flow is not a primary part of the hydrogen safety system since the hydrogen is considered to be adequately contained by the robust hydrogen flask, vacuum vessel, and helium jacket.
2. Exhaust port located near ceiling of cave in location for best neutron shielding.
3. Ventilation rate: 6,000 l/min (200 cfm) (this means that we change air in the cave every 10 min.)
4. Fan motor either explosion-proof or mounted outside air stream. Rotor to be non-sparking construction.
5. Exhaust ducted outside building

EMERGENCY HYDROGEN DISPOSAL

In a case of fire or some other reason it must be possible to dispose of the hydrogen inventory quickly. Proposed: fill vacuum vessel with helium at 1 atm and electrically heat lateral surface of target flask.

Appendix 2 (H. Nann, 6-6-01): Safety Features of the LH_2 Target System

The LH_2 target system consists of three components: a target flask containing the liquid hydrogen, an insulating vacuum vessel, and a helium jacket surrounding the vacuum vessel. All components were designed according to the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and 2; ASME B31.3 Code for Pressure Piping – Process Piping; CGA S-1.3 Pressure Relief Device Standards – Part 3 – Stationary Storage Containers for Compressed Gases. Each component is equipped with a primary relief system of a spring-loaded pressure relief valve and a parallel, secondary relief system of a rupture disc. All pressure reliefs are connected to a large size (6 inch diameter 304L stainless steel pipe) vent line, which is filled with nitrogen at atmospheric pressure, to the outside of the building.

1. LH_2 Flask:
   Material: 5083-O aluminum except for AZ31C-H24 magnesium alloy entrance window; wall thickness 0.10 inch
   A) Design pressure (calculated according to CODE formulae): internal: 160 psia (10.2 atm) - external (0.6 times internal): 96 psia (6.5 atm)
   B) Normal operating pressure: 10.2 psia (0.7 atm); the atmospheric pressure at Los Alamos is 11.2 psia.
   C) Maximum allowable working pressure (internal): 70 psig (4.8 atm)
   D) Relief paths: single 1.5-inch I.D. piping up to pressure relief valve and rupture disk
   E) Relief valve flow capacity: 0.20 lb/s
   F) Pressure relief valve set point: 7 psig
   G) Rupture disk set point: 75 psig

2. Insulating Vacuum Vessel:
Material: 5083-O aluminum except for titanium (grade to be specified later) entrance window; wall thickness 0.10 inch
   A) Design pressure (calculated according to CODE formulae): internal 150 psia (10.2 atm) - external (0.6 times internal): 90 psia (6.1 atm)
   B) Normal operating pressure: vacuum
   C) Maximum allowable working pressure (internal): 70 psig (4.8 atm)
   D) Relief paths: single 2.5-inch I.D. piping up to pressure relief valve and rupture disk
   E) Relief valve flow capacity: 0.50 lb/s
   F) Pressure relief valve set point: 20 psig
   G) Rupture disk set point: 75 psig

3. Helium Jacket:
Material: 5083-O aluminum except for titanium (grade to be specified later) entrance window; wall thickness 0.10 inch
   A) Design pressure (calculated according to CODE formulae): internal 150 psia (10.2 atm) - external (0.6 times internal): 90 psia
   B) Normal operating pressure: 18 psia (1.2 atm)
   C) Maximum allowable working pressure (internal): 70 psig (4.8 atm)
   D) Relief paths: single 0.75-inch I.D. piping up to pressure relief valve and rupture disk
   E) Relief valve flow capacity: 0.05 lb/s
   F) Pressure relief valve set point: 25 psig
   G) Rupture disk set point: 75 psig

Appendix 3 (H. Nann, 6-6-01): Calculations of Flow Rates through the blowoff stacks in the event of catastrophic vacuum or target failure

Calculations based on the Bates Internal Report # 90-02 were performed to determine the size of the relief plumbing such that the mass flow remains subsonic at all times and that the maximum pressure in each component remains well below its bursting point. Based on the formulas and algorithm in this report, two computer programs were written. The first program calculates the mass evolution rate and boil-off time from geometric information and the properties of both the target material and vacuum spoiling gas, whereas the second program yields the maximum pressure occurring during the discharge through the pressure relief system. The information that was used as input to the calculation as well as their results are given in tables 1 and 2. The calculation of the maximum pressure in the target flask and the vacuum vessel during the catastrophic discharge includes all the pipes up to the pressure relief valve. Furthermore, it is assumed that all the mass flows out through the pressure relief system into the vent line to the outside of the building and not through the fill line relief valves. The friction factor for each relief system was taken from a Moody plot. A typical value was f = 0.016. The effective resistance coefficient K_{eff} was calculated for an equivalent length of 500 resulting K_{eff} = 8.0.

Table 1: *Boil-off Rates of 21 Liter of Liquid Hydrogen*

	Target Flask		Vacuum Vessel	
Heat Flux into Target [W/m^2]	13,000*	40,000**	100,000	100,000

Surface area [m^2]	0.50	0.25	0.5	1.0
Boil-off Time [s]	102	66	13.2	6.6
Mass Boil-off Rate [lb/s]	0.032	0.049	0.25	0.49

* *Calculated under the assumption that the target flask is surrounded by air.*
** *10kW of (electrical) power transferred to lateral surface of target flask.*

The final results show that, in the case of a catastrophic vacuum failure to air, the target flask is subjected to a pressure of no more than 43 psia if the inner diameter of the pressure relief piping is 1.5 inch. The maximum pressure in the vacuum vessel for the case of a rupture of the target flask is 40 psia for an inner diameter of the pressure relief piping is 2.5 inch. Both pressures are well below the 100 psia pressures that the target flask and vacuum vessel will be tested at. Since the pressure relief system for the vacuum vessel can respond safely to a possible catastrophic rupture of the target flask, the pressure relief system of the helium jacket does not need to handle a large mass flow rate in the unlikely event of a leak in the wall between the vacuum vessel and the helium jacket. Thus a pressure relief system with an inner diameter of 0.75-inch piping is considered adequate.
Table 2: *Response of the pressure relief system for various mass flow rates and tubing sizes.*

	Target Flask					Vacuum Vessel	
Mass Flow Rate [lb/s]	0.05	0.10	0.05	0.10	0.20	0.50*	0.50*
I.D. of Relief Pipe [in]	1.0	1.0	1.5	1.5	1.5	2.0	2.5
Sonic Mass Flow Rate [lb/s]	0.13	0.13	0.29	0.29	0.29	0.52	0.81
Maximum Pressure [psia]	26.3	48.1	17.3	24.2	43.0	59.8	39.0

* *Mass flow rate when all of the 21 liter of LH2 is at once in contact with the vacuum vessel wall at 293 K.*

In summary, pressure relief systems with a 1.5-inch inner diameter discharge pipe for the target flask and a 2.5-inch inner diameter discharge pipe for the vacuum vessel will respond safely to catastrophic failures. Furthermore, the safety relief piping for the helium jacket will have an inner diameter of 0.75 inch.

Appendix 4 (M. Gericke, 7-1-01): Gas Handling System Operating Procedures

The following is a description of the operation of the GHS, both for preparation (i.e. cleaning the system) and operation during filling and experiment. Except possibly for the initial bake-out of the system, each step in the sequence should be repeated as stated, each time the target cell is to be refilled. The description of each step starts with a listing of the state of each valve in the system and all components like the turbo pump (TP), mechanical pump (MP), etc ... Each component or valve that changes state at least once during the step is then shown in a table, listing the change of state it must undergo in the correct sequence, as the table is read from left to right and top to bottom. The valve/component state list in the next step will reflect the changes performed on the various valves and components in the previous step. Those valves or components that will not change state during a particular step are not listed in the table, but are still repeated in the valve/component list. So no matter where one is in the sequence of steps the state list will always show the correct state each component or valve should be in at that particular time.

The main steps are:

- Section 3: Bake-out
  - 3.1 OPC Bake-out
  - 3.2 PRF Bake-out
  - 3.3 LNT Bake-out
  - 3.4 GHS Bake-out
- Section 4: System purge
  - 4.1 Preparation
  - 4.2 Purge
- Section 5: TC He leak check
- Section 6: Begin Final TC Pump-down with MP
- Section 7: TC filling
  - 7.1 Preparation
    - 7.1.1 Monitor H2 purity
    - 7.1.2 Continue MV and TC Pump-down with TP and switch RGA to leak check on MV
  - 7.2 Fill TC
- Section 8: Continuous TC monitoring and leak checking

3. Bake-out

3.1 OPC Bake-out

State:

Open: none
Closed: V1-V30
TP1: off
TP2: off
RGA: off
LNT: empty

	V21	V23	V13	TP1	Action
Step 1	Open	Open	Open	On	Pump on OPC
Step 2	Close	Close	Close	Off	Stop Pumping

3.2 PRF Bake-out

State:

Open: none
Closed: V1-V30
TP1: off

TP2: off
RGA: off
LNT: empty

	V21	V22	V16	TP1	Action
Step 1	Open	Open	Open	On	Pump on PRF
Step 2	Close	Close	Close	Off	Stop Pumping

3.3 LNT Bake-out

State:

Open: none
Closed: V1-V30
TP1: off
TP2: off
RGA: off
LNT: empty

	V21	V20	V18	V25	V26	V27	V28	V29	TP	Action
Step 1	Open	Open	Open	Open	Open	Open	Open	Open	On	Pump on LNT
Step 2	Close	Close	Close	Open	Open	Open	Open	Open	Off	Stop pumping

3.4 GHS Bake-out
State:

Open: V25-V29
Closed: V1-V24,V30
TP1: off
TP2: off
RGA: off
LNT: empty

	V1	V2	V9	V24	V8	V15	V19	V6	V21	TP2	TP1	Action
Step 1	Open	Open	Open	Open	Open	Open	Open	Open	Open	on	on	Pump on GHS
Step 2	Open	Open	Open	Open	Open	Open	Open	Close	Close	off	off	Stop pumping

4. System Purge

4.1 Preparation

State:

Open: V1,V2,V8,V9,V15,V19,V24-V29
Closed: V3-V7,V10-V14,V16-V18,V20-V23,V30

TP1: off
TP2: off
RGA: off
LNT: empty

	V3	V7	V13	V14	V16	V17	V18	V20	V22	V23
Step 1	Open	Open	Open	Open	Open	Open	Open	Open	Open	Open

4.2 Purge

State:

Open: V1-V3,V7-V9,V13-V20,V22-V29
Closed: V4-V6,V10-V12,V21,V30
TP1: off
TP2: off
RGA: off
LNT: empty

	V9	V24	V10	V11	V30	V4	V6	V21	TP2	TP1	Action
Step 1	Open	Open	Open	Open	Open	Open	Close	Close	Off	Off	Fill system with He to the apprOpenr. HJ Pressure
Step 2	Open	Open	Open	Open	Close	Close	Open	Open	On	On	Pump He through GHS, MV an TC to purge
Step 3	Close	Close	Open	Open	Close	Close	Open	Open	On	On	Pump down MVwith TP1 and T withTP2
Step 3	Close	Close	Open	Open	Close	Close	Close	Open	Off	On	Stop pumping on TC when P = 10E-6 Torr

5. TC He leak check

State:

Open: V1-V3,V7,V8,V10,V11,V13-V23,V25-V29
Closed: V4-V6,V9,V12,V24,V30
TP1: on
TP2: off
RGA: off
LNT: empty

	V9	V1	V4	V23	V22	V3	V7	V20	TP1	RGA	Action
Step 1	Open	Close	Open	Close	Close	Close	Close	Close	On	Off	Fill TC with He, pump MV
Step 2	Close	Close	Close	Close	Close	Close	Close	Close	On	On	Leak check with RGA

6. Begin Final TC Pump-down with MP

State:

Open: V2,V8,V10,V11,V13-V19,V21,V25-V29
Closed: V1,V3-V7,V9,V12,V20,V22-V24,V30
TP1: on
TP2: off
RGA: on
LNT: empty

	RGA	V2	V8	V15	V9	V6	V24	TP1	TP2	Action
Step 1	Off	Close	Close	Close	Open	Open	Open	Off	On	Pump both MV and TC with TP2

7. TC filling

7.1 Preparation
7.1.1 Monitor H2 purity
State:

Open: V6,V9-V11,V13,V14,V16-V19,V21,V24-V29
Closed: V1-V5,V7,V8,V12,V15,V20,V22,V23,V30
TP1: off
TP2: on
RGA: off
LNT: empty

	V19	V23	V29	TP	V7	V5	RGA	LNT	Action
Step 1	Close	Open	Close	On	Close	Close	Off	empty	Pump on H2 Supply line via valve 23
Step 2	Close	Open	Close	On	Open	Open	Off	full	Open H2 supply, Monitor G4 (~10 E-4 Torr), Adjust R1
Step 3	Close	Open	Close	On	Open	Open	On	full	Monitor H2 purity on RGA

1. Continue MV and TC Pump-down with TP and switch RGA to leak check on MV

State:

Open: V5-V7,V9-V11,V13,V14,V16-V18,V21,V23-V28
Closed: V1-V4,V8,V12,V15,V19,V20,V22,29,V30
TP1: on
TP2: on
RGA: on
LNT: Full

	V5	RGA	V7	V23	V19	TP1	V24	V6	TP2	V2	V8	V15	Action
Step 1	Close	Off	Close	Close	Close	Off	Open	Close	Off	Open	Open	Open	Monitor P2 / G4
Step 2	Close	Off	Close	Close	Open	On	Open	Close	Off	Open	Open	Open	Pump on MV until P ~ 10E-4 Torr
Step 3	Close	On	Close	Close	Open	On	Open	Close	Off	Open	Open	Open	Check MV for leaks, Pump MV

7.2 Fill TC

State:

Open: V2,V8-V11,V13-V19,V21,V24-V28
Closed: V1,V3-V7,V12,V20,V22,V23,V29,V30
TP1: on
TP2: off
RGA: on
LNT: Full

	V9	V24	V5	V12	Action
Step 1	Close	Close	Close	Close	Monitor G4,P4,F1
Step 2	Close	Close	Open	Open	Adjust R1, Monitor G4,P4,F1

8. Continuous TC monitoring and leak checking

State:

Open: V2,V5,V8,V10-V19,V21,V25-V28
Closed: V1,V3,V4,V6,V7,V9,V20,V22-V24,V29,V30
TP1: on
TP2: off
RGA: on
LNT: Full

	V5	V10	V6	TP2	Action
Step 1	Close	Close	Open	On	Pump on H2 supply line. Shut off target cell
Step 2	Close	Close	Close	Off	Monitor MV for leaks and maintain vacuum

Final state:

Open: V2,V8,V11-V19,V21,V25-V28
Closed: V1,V3,V4-V7,V9,V20,V22-V24,V29,V30
TP1: on
TP2: off
RGA: on
LNT: Full